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Army Science Conference 2006: TECHNOLOGY ASSESSMENT OF SOLDIER & MAN PORTABLE FUEL CELL POWER

Pavel Fomin*, Elizabeth Bostic, Christopher Bolton, Jonathan Cristiani, H. Scott Coombe, Terry DuBois, and JJ Kowal

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TECHNOLOGY ASSESSMENT OF SOLDIER & MAN PORTABLE FUEL CELL POWER SYSTEMS

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ABSTRACT

In response to the growing need for lightweight - high energy density power sources on the battlefield, the US Army Communications Electronic Research Development Engineering Center (CERDEC) Fuel Cell Technology Team initiated several development contracts to address multiple areas where fuel cell technologies have the potential to offer increased capability to the Warfighter. Two of those areas are Soldier and Man Portable Power. Soldier Power fuel cell technology focuses specifically on Soldier worn power equipment, mainly from the sub to 100 Watt range. Man Portable Power fuel cell technology focuses on larger up to 500 Watt systems that could be carried by one or multiple Soldiers and provide power in remote locations. These two focus areas will serve as the basis of this paper discussing development status as well as testing results.

1. INTRODUCTION

For almost a decade, batteries have served as the primary power source for the Warfighter. From essential communication support to integrated thermal weapon sights and night vision capability, batteries power the vital battlefield functions on which Soldiers depend. However, with recent advances in digital warfare, the modern Soldier's War-Fighting capabilities have exceeded what traditional batteries are capable of supporting. Even advanced battery chemistries, such as lithium–ion rechargeable batteries are only capable of providing a maximum energy density of 145 Watt-hours/kg, with lithium primary batteries limited to 200-230 Watt-hours/kg. As a result, the Soldier carries multiple batteries of various chemistries that impact and complicate the logistic supply chain. To combat the disadvantages associated with traditional batteries and meet the growing power requirements, the U.S. Army CERDEC has been exploring alternative energy sources, including fuel cell technology, in order to provide a lightweight – high energy density power solution.

Fuel cells have shown great promise in the ability to provide power and offer several advantages over traditional batteries. In a fuel cell, a fuel and an oxidant are reacted to provide DC power. As long as a fuel is supplied, a fuel cell has the ability to operate indefinitely. Fuel cells also offer the additional benefits of high efficiency, improved fuel utilization, and low acoustic and thermal signatures.

The benefits of fuel cell technology have prompted CERDEC to evaluate a variety of fuel cell systems as potential power sources for the future Warfighter. CERDEC's mission lies in providing an increased capability to the Soldier through lightweight, high energy density power. This includes both Soldier-worn and larger Man-Portable Systems. To better understand the power needs of the Warfighter, CERDEC supports the Project Manager Soldier Warrior (PM SWAR) Land Warrior and Ground Soldier System programs. As shown in Figure 1, PM SWAR has identified a 400 Watt-hour/kg energy density requirement for the Land Warrior major defense acquisition program. As mission duration increases the specific energy required increases to 1000 Watt-hours/kg for a 72 hour mission. Fuel cells are one of the technologies that may meet future power requirements. CERDEC works closely with PM SWAR to test, evaluate, and transition the technology into appropriate applications.

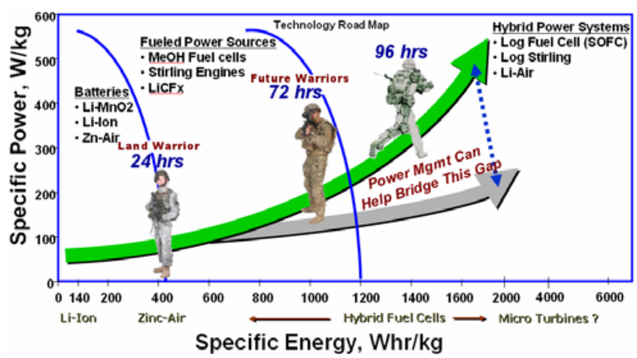

Figure 1 – Soldier Power Requirements

Factors such as required power and application determine which fuel cell chemistries are appropriate for a specific function. For smaller, Soldier portable applications, Reformed and Direct Methanol Fuel Cells (RMFC & DMFC) have been identified as the most promising candidates. Reformed and direct methanol fuel cells are similar in that they both use methanol as the carrier fuel of hydrogen but differ in the way the fuel is processed. DMFCs offer a relatively simple design by eliminating the reforming phase and directly feeding fuel to the stack. RMFC reforms methanol into a hydrogen rich stream before feeding the fuel to the stack. This requires a methanol/water fuel mixture creating a more complicated

system but one that could be more tolerant of extreme cold weather conditions.

In order to determine which technology best meets the needs of the Warfighter, CERDEC has evaluated both DMFC & RMFC technologies. From 2003 to 2005, CERDEC contracted with Smart Fuel Cell (SFC) of Brunnthal, Germany to develop a lightweight Soldier-worn 20 Watt DMFC hybrid system. Until recently, their most advanced system, the C20-MP was capable of instantly providing 20 Watts for a period of 24 hours using a single 500 ml cartridge of pure methanol. Based on CERDEC's test and evaluation, the C20-MP has an energy density of 430 Watt-hours/kg for a 72-hour – 20 Watt mission. PM Soldier Warrior has taken great interest in the recent progress of SFC and initiated a Defense Acquisition Challenge Program (DACP) to further develop the C20-MP to a more lightweight and vertical form factor referred to as the M-25. The final system is projected to have an energy density of greater than 700 Watt-hours/ kg for a 72-hour mission.

CERDEC is also evaluating RMFC technologies through a development contract with UltraCell Corporation of Livermore, California. UltraCell is developing a lightweight Soldier-worn 20 Watt RMFC system. The initial XX90 model units are capable of providing a constant 20 Watt power output with a net system efficiency of 23% and an energy density of 315 Watt-hours/kg. Because the XX90 reforms methanol, the fuel reformer needs to reach appropriate temperatures before fuel can be fed into the stack; creating a start up time of approximately 13 minutes. CERDEC recently took delivery of next generation UltraCell XX25 EVT units. These units offer advanced user control as well as increased packaging for military ruggedization.

In addition to the evaluation of Soldier power sources, CERDEC is also examining larger, Man Portable fuel cell systems for military applications. Currently, Soldiers are dependent on vehicle or base power for charging, leaving a recharge capability gap in forward field environments. This is especially difficult when dealing with multi-day missions and the need to return "dead weight" discharged batteries back to the base. To meet the Soldier's recharging needs; CERDEC initiated a development contract with IdaTech, LLC of Bend, Oregon to develop a 250 Watt RMFC Portable Power Supply called the iGen™. CERDEC took delivery of the first generation unit in the spring of 2005, the second in mid October 2005, and the most recent generation in June 2006. The iGen™ operates on a methanol/water fuel mixture with a net system efficiency of 15.1%. IdaTech has estimated that next generation units will provide system efficiencies from 20 – 25%, making the unit more practical for field battery recharging.

2. CERDEC TEST PROCEDURE

US Army CERDEC testing procedures call for a variety of system and environmental evaluations totaling in twelve individual tests. When applicable, tests were repeated multiple times to ensure accuracy as well as adherence to testing procedure. The twelve individual tests can be grouped into the following four main categories: Fuel Consumption, Electrical Characterization, Orientation, and Environmental Testing. Data was logged both manually and electronically to prevent data loss and verify results. When applicable, internal component measurements were taken, however to maintain confidentiality agreements, only specific system information will be disclosed.

3. SOLDIER POWER SYSTEMS

Two Soldier Power technologies have demonstrated significant advances with respect to technology maturity and system level performance; UltraCell and Smart Fuel Cell.

3.1 UltraCell XX25 EVT

As noted earlier the XX25 EVT is the latest generation 20 Watt reformed methanol system manufactured by UltraCell of Livermore, California. As seen in Figure 2, the system has a dry mass of just over 1.15 kg with system dimensions of 5.38'' X 1.80'' X 9.30''. Fuel is supplied via re-fillable 250cc cartridges that have a mass of 0.34 kg each. Since May of 2006, CERDEC has a received a total of ten (10) XX25 EVT units. The first three units experienced firmware issues and were recalled by UltraCell, while systems 4, 5 and 6 required fuel processor upgrades. For this reason, the majority of test results are from the four most recent units, referred to as units 7, 8, 9, and 10.

Figure 2 – UltraCell XX25 EVT Fuel Cell and Fuel Cartridge

Because the XX25 EVT is a reformed methanol fuel cell, the system requires a methanol/water fuel mixture for operation. The fuel is a 61.8 wt% mixture of methanol and water. When the unit is turned on, fuel is sent to the fuel processor heating it to approximately 280ºC and the fuel cell stack to 165ºC. Then reformate is produced and fed to the stack along with air to produce DC power. The start up process, during which the system reaches operating temperatures, takes 26.94 minutes and consumes 19.31 grams of fuel on average. At this point the system is operational and can accept a load from the user. UltraCell is redesigning the start up process to potentially include an internal battery large enough to handle user loads as the fuel cell is warming up providing instant power to the user.

Initial polarization of the XX25 EVT shows that once operating conditions are met, the open circuit voltage stabilizes at 16.72 V. As user load is increased voltage begins to decrease slightly to 16.5 V at 20 Watts. It is important to note, that the XX25 EVT is capable of operating at 25 Watts for limited periods of time. Figure 3 shows a graph of the polarization curve.

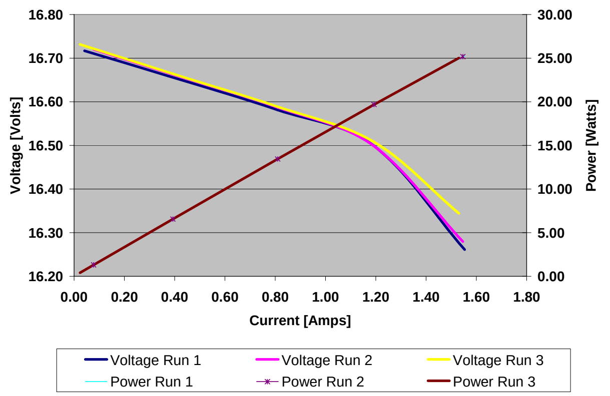

Figure 3 - UltraCell XX25 EVT Initial Polarization

At rated 20 Watt power output, the XX25 EVT produces on average a net system efficiency of 23.16% with respect to the lower heating value (LHV) of methanol. The highest single run recorded efficiency was exactly 25.0% during a seven (7) hour 20 Watt fuel consumption test. Efficiency of the system is calculated by comparing the net power produced in watts to the energy potential of the fuel. If the fuel is a methanol/water mixture, the fuel weight percent is used to calculate the fuel energy potential. The system efficiency (η_{sys}) can be written as:

$$\eta_{sys} = \frac{(powerconsumed(watts)) * (timeoftest(hours))}{LHVMeOH * MeOHwt\% * (fuelconsumed(grams))} * 100 \quad (1)$$

In order to maintain internal operating conditions regardless of user load, as system power decreases so does efficiency. Figure 4 shows the net system efficiency at various loads of 25%, 50%, 75% and 100% of system rated power. Four of the UltraCell units operated best at higher loads, specifically above 50% rated power output. As the load was reduced to below 50% of the rated power or 10 Watts, the effect from thermal loss was clearly visible by the steep drop in efficiency.

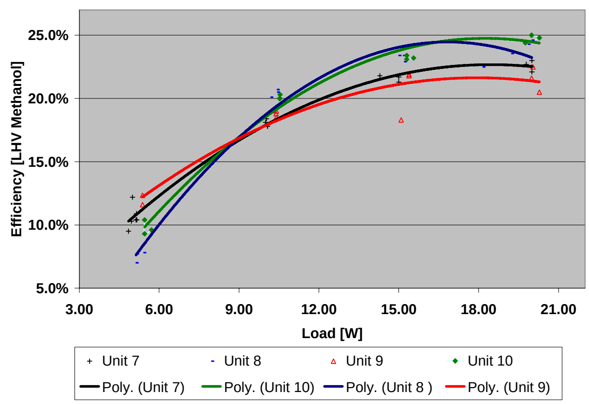

Figure 4 - UltraCell XX25 EVT Net System Efficiency

Because system efficiency is directly correlated to fuel consumption, similar user load behavior is confirmed with respect to fuel consumption. Figure 5 shows that as user load decreases from 20 to 5 Watts, hourly fuel consumption is only minimally effected and overall fuel consumption remains close to that at full rated power. This again is due to the need to maintain balance of plant (BOP) components as well as manage thermal losses.

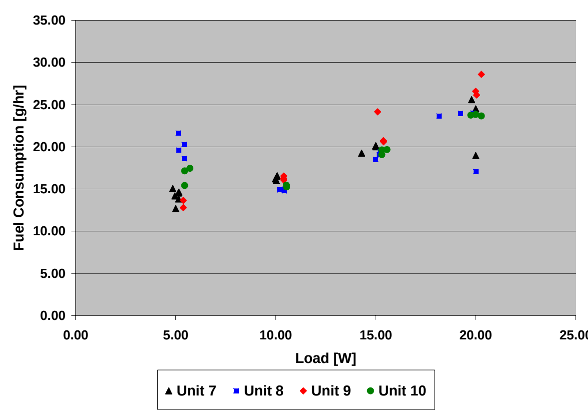

Figure 5 - UltraCell XX25 EVT Fuel Consumption

Given the above system efficiencies and fuel consumption rates, it is possible to calculate energy density for a 3 day (72 hour) mission where the average hourly power consumption is 20 Watts. The average 250cc fuel cartridge weighs 0.34 kg and contains 0.22 kg of fuel providing just over nine hours (9.07) of operational runtime at 20 Watts. Including the 19.31 grams required for start up and assuming only one start up for the entire mission, the soldier will need nine (9) 250cc cartridges amounting to a fuel weight of 3.08 kg. When that is added to the system

weight of 1.15kg, the total 72 hour mission weight is equal to 4.23 kg providing 340 Watt-hours/kg. It is important to note that although the current fuel cartridge configuration has not yet been optimized for military applications, an energy density surpassing lithium ion as well as lithium primary batteries has been demonstrated. This provides a clear capability increase to the Soldier.

The CERDEC test plan also calls for a series of relative environment testing aimed at evaluating the feasibility of field deployment in various environments. Figure 6 displays XX25 EVT thermal signatures at an ambient 20ºC environment.

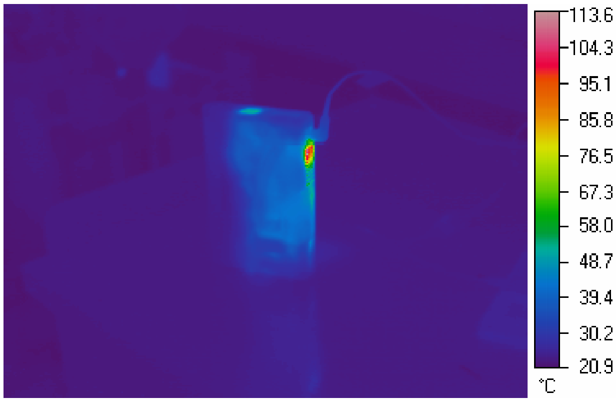

Figure 6 – UltraCell XX25 EVT Thermal Signatures

3.2 Smart Fuel Cell M-25

In late 2005, Program Executive Office (PEO) Soldier initiated a Defense Acquisition Challenge Program (DACP) with DuPont and Smart Fuel Cell to develop the next generation Soldier power source. The program was designed to leverage existing CERDEC technology and develop a higher technology readiness level with specific emphasis placed on human factors. The final deliverable, the M-25 is expected in 2007 and targets an energy density of greater than 700 Watt-hours/kg with a system weight of less than 0.7 kg. DuPont and SFC have provided early generation prototype units of the M-25, referred to as the Fuel Cell Power System (FCPS) to Natick Soldier Center (NSC) and CERDEC.

As shown in Figure 7, the M-25 first generation prototype unit, the FCPS utilizes a highly vertical form factor similar to the Land Warrior Li-145 battery. Fuel is supplied to the system via a flexible metallic hose attached to a fuel pump. The hose is then attached to a fuel cartridge, in this case a 500 milliliter container of pure (neat) methanol.

Figure 7 – SFC FCPS

The FCPS has a system mass of 1.18 kg including the cartridge connector and system dimensions of 2.31’’ X 3.06 ’’ X 9.75’’. The 500 ml pure methanol fuel cartridge has a mass of 0.47 kg.

The FCPS is a Direct Methanol System and there are several differences between RMFC and DMFC worth noting. In order to maintain the proper methanol/water concentration being fed to the anode side of the stack, an internal water reservoir needs to be maintained. This is done automatically once the unit reaches operating state but requires the addition of approximately 30ml of a methanol/water “process medium” mixture prior to initial startup. This is done as part of the preparation procedure for first time operation only and should not need to be performed in the future. Under the current design the unit comes with a four (4) cell lithium polymer 800 mAh battery that attaches to the bottom of the fuel cell and has a mass of 110 grams. The battery is scaled to power the pumps and fans and also to provide immediate output power capable of meeting a user load of 20 Watts. This eliminates a long start up time and can provide instant power at the push of a button. At this point, the system operates just like a battery. The fuel cell stack reaches a temperature of 65°C at steady state operation. Full output power is achieved after 2-5 minutes after start-up.

The polarization graph in Figure 8 shows that the FCPS has an open circuit voltage of 16.55 V. This voltage remains fairly stable and only shows significant change when the power draw exceeds 20 Watts, at which point the voltage decreases to 15.8V.

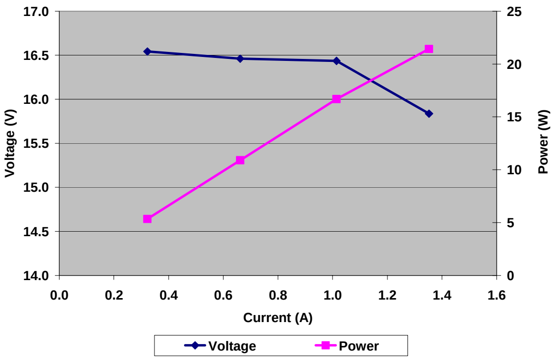

Figure 8 – FCPS Initial Polarization

With respect to system efficiency, as seen in Figure 9, the FCPS unit achieved an average of 22.4% at a constant 20 Watt load, including initial start-up and start up battery recharge.

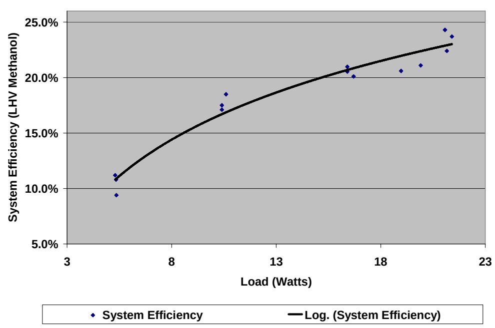

Figure 9 – FCPS System Efficiency

As with past SFC DMFC systems, as system load decreases so does efficiency. The same can be said with regards to fuel consumption as represented in Figure 10. At a full rated constant 20 Watt power draw, the FCPS consumed on average 21.00 ml/hr of pure methanol. When the load was lowered to 5 Watts, fuel consumption decreased to 11.77 ml/hr reducing the overall net system efficiency to 10.5%. This is due to one of the fundamental principles of DMFC systems. Although the efficiency of the fuel cell stack increases at lower power, the parasitic losses of the active and electronic components lead to overall lower system efficiency.

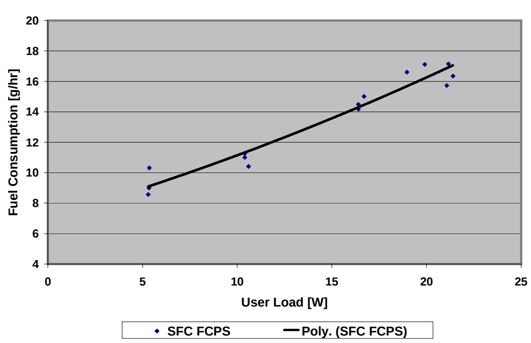

Figure 10 – FCPS Fuel Consumption

Figure 11 displays the FCPS thermal signatures at 20 ºC ambient environment.

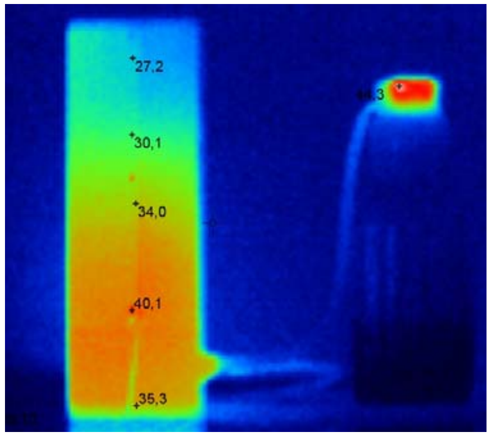

Figure 11 – SFC FCPS Thermal Signatures
(Courtesy of Smart Fuel Cell)

Because the FCPS operates on pure methanol and recycles water, SFC is capable of placing maximum potential energy into their fuel cartridges. Under the current configuration, for a three (3) day, 20 Watt power draw mission; three (3) 500ml fuel cartridges are required. When the weight of the three cartridges is added to the system weight, a total weight of 2.60 kg is needed for the mission providing an energy density of 554 Watt-hours/kg. This high energy density is in part due to fuel cartridge configuration. Because SFC optimized each fuel cartridge for 24 hour 20 Watt load operation, they were able to reduce redundant weight and provide an overall higher energy density. Generally, fewer cartridges require less dry weight increasing the system energy density.

3.3 Soldier Power Conclusions

Both UltraCell and Smart Fuel Cell have made significant progress in the past 18 months. A total of 137 run hours have been placed on the FCPS unit and approximately 100 hours on each of the XX25 EVT units at the time of this report. Manufacturers of both systems claim run hours in the thousand(s) range before critical repair or maintenance is required. Furthermore, throughout the course of testing it was not uncommon for CERDEC test engineers to experience various faults with both systems ranging from water leaks, to fuel priming errors, to various user design issues resulting in fuel delivery and cartridge component wear. Since these systems are not at production level quality and are still in the prototype phase, many of these faults stem from engineering causes versus technological barriers. Both UltraCell and SFC have made significant progress in the development of their Soldier power systems and addressing the CERDEC FY08 Soldier Power goals of a technology readiness level (TRL) 6, packaged fuel, 700 Watt-hour/kg, and 0.68 kg dry weight system.

Even though batteries deserve the earned reputation of providing reliable power in the most severe environmental conditions, it is clear to see that as mission duration increases the weight associated with batteries becomes difficult to manage. For shorter mission duration, typically less than 24 hours, batteries offer a more attractive solution than fuel cells in terms of weight and available energy. It is with multi-day missions where Fuel Cells show their true benefit. As seen in Figure 12 below, where mission duration was compared to mission weight for a 20 Watt continuous power draw. Fuel cell technology begins to show a weight advantage at just over 14.5 hours mission duration.

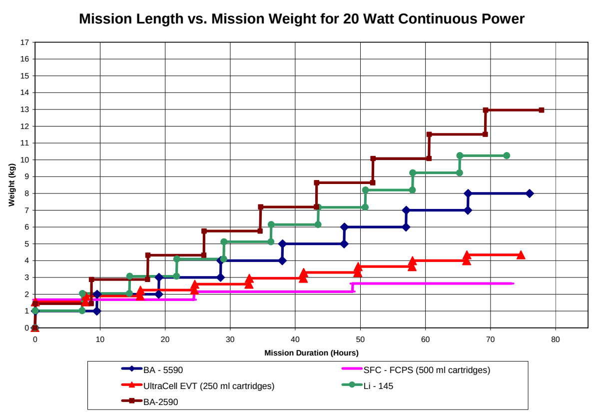

Figure 12– Mission Duration vs. Length Comparison

4. MAN PORTABLE POWER

In addition to the Soldier Power focus area, CERDEC has identified a 100-500 Watt Man Portable Power focus area aimed at bridging a capability power gap. Currently, when soldiers are away from their Tactical Operations Center (TOC) or vehicles, they do not have the ability to recharge batteries. This causes the typical Soldier to carry multiple batteries of various chemistries that must then be returned to the base or vehicle for charging. This not only adds a significant weight burden on the Soldier but also complicates the logistic supply chain through the need to supply batteries of different chemistries out to the field. To bridge this power gap, CERDEC has pursued several development contracts for a 250 Watt Man Portable Battery Charger that could be forward deployed in the field and provide needed power for extended missions. To date, Idatech LLC of Bend, Oregon has shown the highest level of system level development and maturity of a stand alone battery charger.

4.1 IdaTech iGen™ – III Portable Power Supply

CERDEC initiated a development program with IdaTech for a Man Portable Fuel Cell Battery Charger in 2004. The first generation prototype was delivered in the spring of 2005 and the second generation in October of 2005. CERDEC continued the development contract and took delivery of two (2) third generation units in June of 2006.

The IdaTech iGen™ III utilizes RMFC technology operating on a 61.8 wt% methanol/water fuel mixture. As shown in Figure 13, the two units (Units 1 and 2) have a dry weight of 15.09 and 15.34 kg respectively and system dimensions of 13.50'' X 6.25'' X 19.13''. Differences in system weight are due to prototype builds and hand manufacturing. The mass of the system also excludes the mass of the start up battery. As shown in Figure 14, the current configuration specifies the need for a "customer battery" that works as a hybrid with the fuel cell and simultaneously provides start up power. A start up battery would ultimately need to be incorporated for self sufficient operation.

Figure 13 – IdaTech iGen™ – III

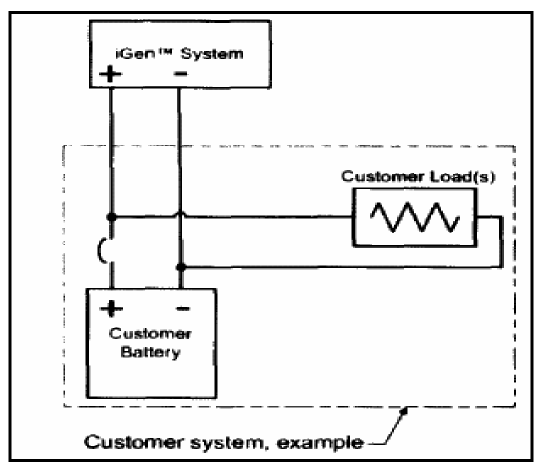

Figure 14– IdaTech iGen™ – III Set-Up

Some additional upgrades from the previous generation unit include a fuel discharge return line used to eliminate air bubbles and maintain constant fuel flow as well as a water drain located in the back of the unit as pictured in Figure 15.

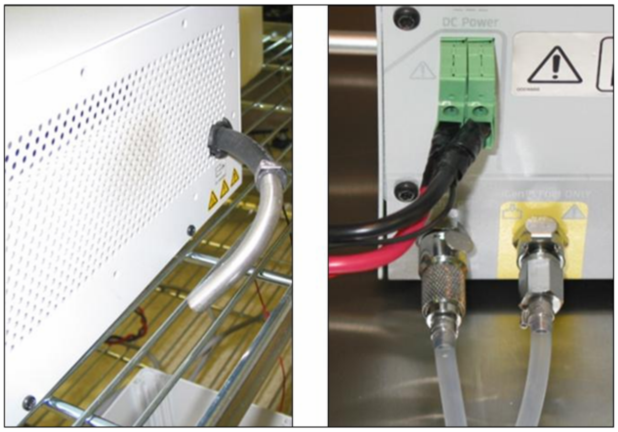

Figure 15 – IdaTech Water Drain and Fuel Discharge

Like many fuel cell systems, the IdaTech iGen™ unit needs to reach optimal operating temperatures before providing output power. This process takes on average 23.5 minutes and consumes 0.082 kg of fuel. Depending on the capacity of the customer battery, power may or may not be provided during fuel cell start up.

As noted earlier, system configuration was set up as described in Figure 14 utilizing a customer battery and ultimately creating a battery / fuel cell hybrid power source.

As shown in Figure 16, the iGen™ III has an open circuit voltage of 13.5V. Even when full load was applied the voltage only decreases slightly and stabilized at 12.7V. This behavior is a result of the hybrid customer battery system configuration. The system is set up to operate as a battery charger and maintain a float voltage of approximately 13.5V. If the user load is less than the maximum output of the system, the system will charge the battery and maintain the float voltage. Although it is not visible from this graph, the iGen™ units were not capable of sustaining a full 250 Watt load for prolonged periods of time. When CERDEC test engineers attempted to operate the unit at full rated power for greater than several hours, specific cell voltage and system shutdown errors were encountered.

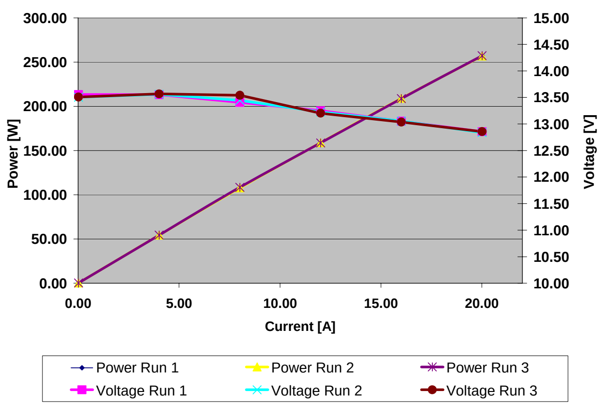

Figure 16 – IdaTech iGen™ – III Initial Polarization

With respect to efficiency, the average recorded maximum efficiency was 15.10% and 13.53% for Units 1 and 2 with respect to LHV of methanol. The single highest recorded efficiency was demonstrated by Unit 1 during a 200 Watt fuel consumption test where the systems achieved a net efficiency of 15.4%. A detailed representation of efficiency at various loads can be seen in Figure 17.

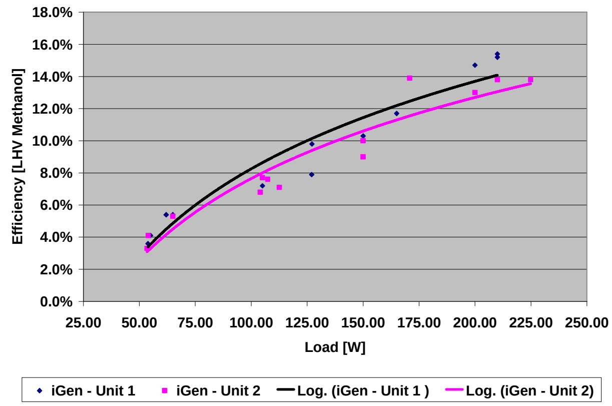

Figure 17 – IdaTech iGen™ – III System Efficiency

Fuel consumption was measured for both units and it was determined that fuel consumption, regardless of load remained in a similar range. This would imply that under the current configuration, the iGen™ - III units are not optimized for load following. The average fuel consumption for Units 1 and 2 was 486.08 and 534.97 ml/hr at 200 Watts and 463.26 and 474.70 ml/hr at 60 Watts net power output. Additional fuel consumption data is represented in Figure 18.

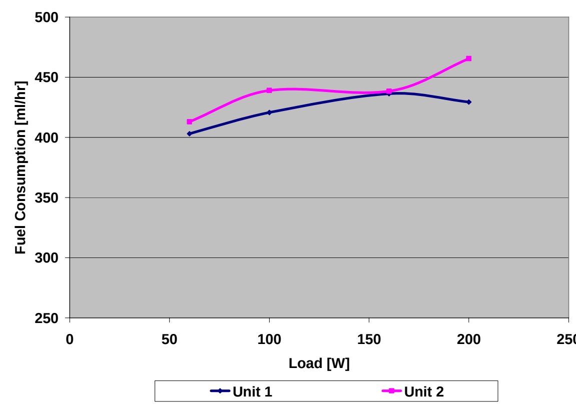

Figure 18 – IdaTech iGen™ – III Fuel Consumption

At the end of fuel consumption testing, CERDEC had placed over 240 operational run hours between the two units and commenced electrical characterization and orientation testing.

With standard electrical characterization testing, fuel cell voltages are measured to analyze the voltage rises and dips during various shifts in user loads. This provides the user

specific system performance specifications and helps assess the feasibility of military application. With regards to these particular units, due to a hybrid battery configuration, the typical voltage fluctuations were not witnessed. The customer battery helped suppress voltage fluctuations and provided a relatively stable output as seen in Figure 19. The iGen™ III did exhibit certain difficulties with respect to maintaining a full 250 watt load. The fluctuations in Figure 19 represent specific user loads in three step application of 100%, 75%, 50%, 25%, and then 100% load in between rest loads of zero (0) Watts.

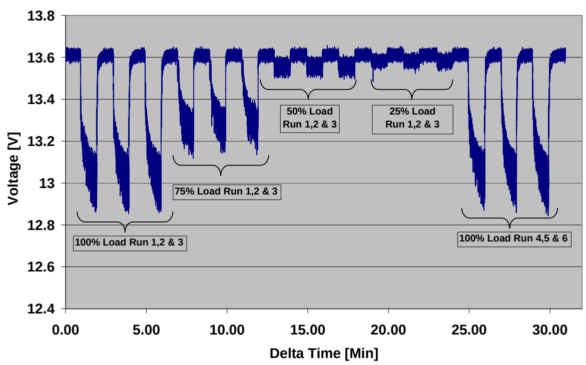

Figure 19 – IdaTech iGen™ – III Electrical Characterization DT = 1 min

Both of the iGen™ units were evaluated for orientation independence. During this testing both units were rotated and elevated for startup and load operation 90 º in both the right and left direction. Both units showed no errors and operated at the respected load without any degradation in efficiency or increase in fuel consumption. Figure 20 shows the units in both the left and right incline

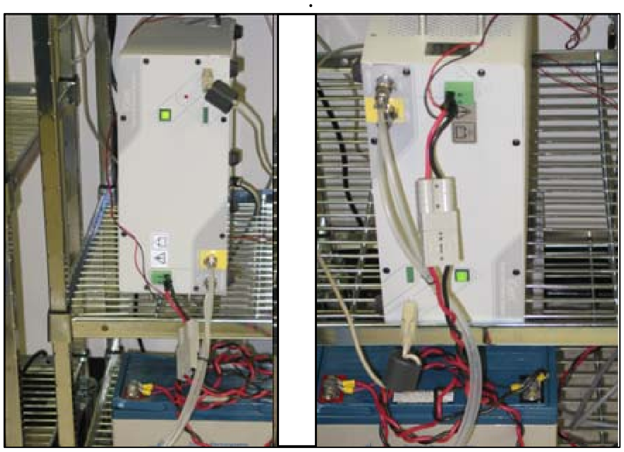

Figure 20 – IdaTech iGen™ – Orientation Independence

Environmental evaluation was commencing at the time of this report, the Figure below shows iGen™ thermal signatures at a 20 ºC ambient environment.

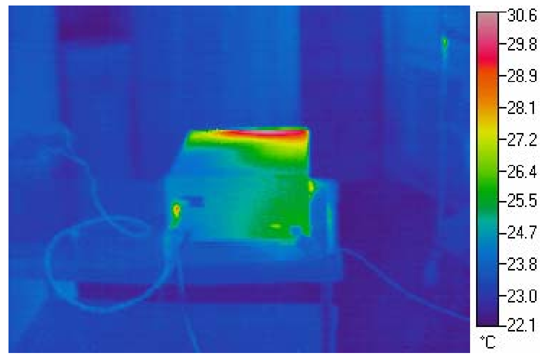

Figure 21 – IdaTech iGen™ -III Thermal Signatures

4.2 Man Portable Power Conclusions and Future Developments

Overall, both of the IdaTech units operated well under limited conditions. At the time of this report, 240 operational run hours have been placed between the two units and relevant environmental testing was beginning to commence.

To better meet user demand and achieve true man portability, IdaTech has been evaluating a more modular approach that would involve separating the Man Portable Charger into a two box configuration. Design details are still being finalized but preliminary analysis specifies the possibility of creating individual package housing for the fuel cell and processor. This would reduce the overall system weight as well as the weight each soldier would have to carry.

5. CONCLUSIONS

As a greater amount of technology is transitioned to the front lines, power is an increasingly limiting factor in mission capability. Recent advances in both the Soldier and Man Portable Fuel Cell areas have shown several advantages of fuel cells versus traditional power systems. CERDEC will continue to play its key role in developing future power sources that will meet the growing power demand and transition technology to the Warfighter quicker.